

Amendment to the Specifications: Pages 1-45

APPLICATION FOR UNITED STATES LETTERS PATENT

Title: Please amend title from "Performance Monitoring of Offshore Petroleum Risers Using Optical Strain Sensors" to: "Dynamic Performance Monitoring of Long Slender Structures Using Optical Fiber Strain Sensors"

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Description

[0001] This application claims priority from U.S. Provisional Patent Application No. 60/441,703, filed Jan. 23, 2003 entitled "Fiber Optics Strain Measurement On Composite Tubulars", herein incorporated by reference in the entirety.

FIELD OF THE INVENTION

[0002] ~~The present invention relates to a fiber optics system which provides the capable to measure in situ the strain in a long steel or composite tubular such as a riser used in offshore petroleum drilling and production operations and, more particularly, through engineering interpretation of the strain data to predict the fatigue life of the tubular and allow active~~

~~controls to be used to mitigate damage from Vortex Induced Vibrations (VIV) imposed by ocean currents.~~

The present invention relates to a fiber optics system which provides the capable to measure in situ the vibration characteristics of long slender structures excited by dynamic disturbances imposed by water or wind generated loads. Long slender structures include, but are not limited to composite or metal risers and tubing used in offshore petroleum industry drilling and production operations and large ropes and cables. For example, the method can be used to measure the magnitude, period, and frequency of Vortex Induced Vibrations (VIV) of risers used in offshore petroleum drilling and production operations; and more particularly, through engineering interpretation of the bending strain data to predict the fatigue life of the tubular and to allow active controls to be used to mitigate the potential damage from VIV. In addition, the fiber optics system can provide bending strain information which can be used to predict the life of spoolable pipe and the onset of buckling induced lock-up during deployment into a small diameter annulus.

BACKGROUND OF THE INVENTION

[0003] Highly successful exploration and production of oil and gas in recent years from deepwater Gulf of Mexico (GOM) and other parts of the world have generated high interest in leasing, exploring and developing deepwater petroleum resources. Deepwater presents many new challenges with the design

of long slender structures such as marine risers in which the length of the structure is significantly greater than the other two dimensions.~~risers~~
Marine rises are especially susceptible to the potentially damaging,
~~including the effects of~~ dynamic disturbances such as Vortex Induced Vibrations (VIV).~~, being an extremely important factor.~~ Risers used in offshore drilling and oil and gas production provide a critical safety function as well as protecting ~~protection to of the environment from oil spills.~~ These long slender tubular structural elements must operate reliably in the harsh marine environment, sometimes for decades. As the water depth of exploration and production operations has increased, so has the challenge imposed on the design and reliability of risers and other long slender structures subjected to vibrations induced by water and wind induced loads. Corrosion or damage can occur, and VIV can impose excessive stress and fatigue damage.~~and high temperature can also become an issue.~~ The capability to inspect and monitor long slender structure ~~riser~~ dynamic performance has therefore become an important technology issue; particularly when the inspection must be conducted in situ.

[0004] Although steel has been the material of choice for risers for decades, composite and titanium risers are increasingly gaining attention because of the weight and economic advantages they provide in deepwater. The composites and oil industry have supported research and development on composite risers for over twenty years and although many believe the

technology is ready for deployment, the expectation has not yet been fulfilled except in isolated trial deployments. Discussion of issues associated with the introduction of composite risers into service can be found in the following references, which are incorporated herein by reference: Douglas B. Johnson, Donald D. Baldwin, and K. Him Lo: "Composite Production Riser Development and Qualification Test Results," Composites for Offshore Operations - 3, S. S. Wang, J. G. Williams and K. H. Lo, Eds. University of Houston - CEAC, 2001, pp. 109-123 and by J. Murali, M. M. Salama, O. Jahnsen, and T. Meland: "Composite Drilling Riser - Qualification Testing and Field Demonstration," Composite Materials for Offshore Operations - 2, S. S. Wang, J. G. Williams, and K. H. Lo, Eds., American Bureau of Shipping, 1999, pp. 115-128. Probably the most important factor limiting the acceptability of this needed service is the reluctance of regulatory agencies to approve introduction of such safety critical component without the accompaniment of reliable methods for inspection. The oil and composites industries ~~likewise~~ recognize the need for proven inspection methods to accompany into offshore service new safety critical applications such as composite risers. Likewise there is a need to monitor the safety of large diameter ropes used for station keeping of offshore platforms and of large cables commonly used in civil engineering structures subjected to water or wind induced vibrations. Discussion of issues associated with Vortex Induced Vibrations in this type of long slender structure can be found in the following reference, which is incorporated

herein by reference: J. Kim Vandiver and O. M. Griffin: "Measurements of the Vortex Excited Strumming Vibrations of Marine Cables," Ocean Structural Dynamics Symposium, Corvallis, Oregon, September 1982.

[0005] Vortex Induced Vibrations (VIV) is a~~one~~ very important design constraint imposed in the design of ~~introduced for deepwater risers is~~ ~~Vortex Induced Vibrations (VIV) and~~ one must address the effect it can have on the fatigue life ~~of risers, particularly metal risers, particularly metal risers.~~ Discussion of some of the design issues associated with VIV in risers can be found in the following references, which are incorporated herein by reference: S.S. Wang, X. Lu, and T.P. Yu: "Vortex Induced Vibrations (VIV) of Composite Production Risers," Composites for Offshore Operations - 3, S. S. Wang, J. G. Williams and K. H. Lo, Eds. University of Houston - CEAC, 2001, pp. 199-213 and by J. Kim Vandiver: "Research Challenges in the Vortex-induced Vibration Prediction of Marine Risers", Proceedings of the Offshore Technology Conference, Paper No. 8698, Houston, May 1998. Although metal components have established methods of inspection when there is ready access, in situ methods are not ~~as~~ well established or available. Composites exhibit different failure modes than metals and have different physical characteristics and specialized inspection methods such as ultrasonic, radiography, and acoustic emission have been used; however, they do not address the need to make deepwater in situ measurements. ~~VIV is also a design concern for composite risers.~~ The availability of in situ Non-

Destructive Evaluation (NDE) monitoring techniques for high performance safety critical ~~components~~ long slender structures such as risers is urgently needed in the petroleum industry to accelerate the acceptance of composites technology and to address safety and reliability concerns for both metal and composite components. Information concerning the vibration characteristics and maximum bending strains being imposed on risers would permit intervention using active avoidance methods or help to improve design solutions such as described in the following reference, which is incorporated herein by reference: J. Kim Vandiver, K. Vikestad and C. M. Laren: "Norwegian Deepwater Riser and Mooring: Damping of Vortex-Induced Vibrations," Proceedings of the 2000 Offshore Technology Conference, Paper No. 11998, Houston, TX, May 1-4, 2000. U. S. Patent 6,401,646 to Masters, et al. describe the application of shrouds, strakes and fairings to reduce the dynamic effects of Vortex Induced Vibrations on pipes immersed in a fluid, which is incorporated herein by reference.

[0006] One very effective way of monitoring structural performance is to measure the strain response to load. Strain can be compared to design predictions and monitoring the change in strain during service can be a very effective indicator of structural degradation due to overload, impact, environmental degradation or other factors. Advanced F~~f~~iber optics technology is a reliable ~~shows promise to provide a reliable~~ in situ method not only to measure ~~not only~~ peak strain values but bending strain

information can For example, the method can be used to measure the
magnitude, period, and frequency of Vortex Induced Vibrations (VIV) of
risers used in offshore petroleum drilling and production operations; and
more particularly, through engineering interpretation of the bending strain
data to predict the fatigue life of the tubular and to allow active controls
to be used to mitigate the potential damage from VIV. In addition, the
fiber optics system can provide bending strain information which can be used
to predict the life of spoolable pipe and the onset of buckling induced
lock-up during deployment into a small diameter annulus. ~~also~~ be used to
determine the ~~dynamic~~-vibration response imposed during ~~VIV~~-dynamic loading
due to strong ocean currents such as by Gulf of Mexico loop currents.
Bending strain is represented by the difference in the strain along the
longitudinal axis measured at opposite ends of an imaginary line drawn
perpendicular to the longitudinal axis of the long slender structure and
through the structure centroid. The maximum bending strain occurs on an
axis perpendicular to the structure longitudinal axis and perpendicular to
the axis of zero bending strain. Fiber optics technology including Optical
Time Domain Reflectometry (OTDR), Optical Frequency Domain Reflectometry
and Bragg defraction grating methods are ideally suited for in situ
measurement of strain in long slender structures. ~~riser strain and~~
~~temperature.~~ Bragg gratings are particularly valuable for making local
strain ~~and temperature~~ measurements while the Optical Time Domain
Reflectometry method is ideally suited for making global strain

measurements such as the average strain over the length of a riser or
several risers.

[006 A] Fiber optics technology has matured rapidly in recent years with emphasis for use both in communications and for structural monitoring. U.S. Pat. No. 6,550,3432 to Croteau, et al. disclose a non-intrusive method for measurement of the flow characteristics of a fluid in a pipeline based on an apparatus for varying the gain (sensitivity) of an fiber optic sensor using a circumferential strain attenuator. U.S. Pat. No. 6,271,766 to Didden, et al. discloses a fiber optics sensing system focused on the measurement of pressure, temperature, liquid fraction, flow, acoustic, seismic, resistivity, corrosion, and pipe wall build-up. The system records the data in a manner which allows selective billing only for the specific measurement services provided. U.S. Pat. No. 5,649,035 to Zimmerman, et al. discloses a fiber optics strain gage patch which measures the local strain response of a structure like a bridge. The strain gage is constructed of circumferential loops of an optical fiber to increase the strain measurement sensitivity and uses OTDR instrumentation to measure the strain.

[0007] An OTDR is a time of flight method which measures spatial positions along an optical fiber by launching brief pulses of laser light into one end of the fiber and then detecting the subsequent reflections at

~~physical~~reflective interfaces inserted along the length of the fiber. The principles of the use of optical fibers technology to measure strain are well established. Discussion of OTDR principles can be found in the following reference, which is incorporated herein by reference: M. K. Barnoski, M. D. Rourke, S. M. Jensen, and R. T. Melville: "Optical Time Domain Reflectometer," Applied Optics, Vol. 16, No. 9. September 1977. The optical fiber is rigidly attached to the long slender structure and thus experiences strain identical to that imposed on the structure. By measuring the transit time of the reflected pulses and by knowing the speed at which light travels in the optical fiber, a very accurate measure of the distance to each reflective interface can be obtained. If ~~a~~As the gauge section defined as the length between two reflective interfaces placed within the optical fiber undergoes a strain, ~~hence changes~~ the interface's spatial position along the fiber changes and the OTDR measurement of ~~this~~ change in length is a direct measurement of the average strain in the structural component. An OTDR with a picosecond pulsed light source can measure a change in length as small as 0.4-inch with an accuracy of about ± 0.001 inch. A change in length of 0.4 in a 70-ft riser converts to a strain of $0.05\% \pm 0.001\%$, which is sufficiently accurate to measure strains in the expected range of 0.07%. If needed, the accuracy can be increased in the riser application by making more than one traverse loop along the length of the pipe and thus provide a longer gage length. A single optical fiber can be used to measure strains at more than one location by imposing ~~multiple~~

reflective surfaces along the length of the optical fiber in combination with customized software algorithms to measure strain between each adjacent reflective interface. Measurement of the longitudinal strain in ~~the~~ a long slender structure composite tube provides valuable information about the state of the "fitness for service" ~~of the composite tube~~ when compared to design allowables and expected conditions.

[007A] Although OTDR and Bragg diffraction are the preferred methods for making strain measurements, other optical fiber methods can also be used including Optical Frequency Domain Reflectometry (OFDR). The primary use of OFDR is for measuring reflections in optical fiber networks. In an OFDR instrument, the optical frequency of the signal laser is modulated in a periodic manner. The OFDR instrument uses an internal reflection to provide a reference of the modulated output. Light reflected from interfaces in the fiber returns to the ORDR, and these light signals are mixed with the reference signal, producing a mixture of optical frequencies. The waveform resulting from this frequency mixture is then analyzed using Fast-Fourier Transfer (FFT) signal analysis. This analysis provides information on the spatial positions of the each reflectance. The primary advantages of the OFDR technique are the excellent signal-to-noise and dynamic range characteristics.

[0008] Vortex-induced dynamic motion imposed by ocean currents typically

have a period greater than 2 seconds and a wavelength involving several lengths of riser. Both the OTDR and Bragg ~~diffraction~~ ~~grating~~ techniques can be used to measure the bending strains imposed by VIV on offshore marine risers. ~~however, the OTDR method is considered to be the preferred method.~~ With the OTDR method, the measured bending strains will have a value which ~~is representative of~~ can be interpreted to calculate the average radius of curvature. Although monitoring a single riser at a critical location may be sufficient, several risers segments at selected locations along the entire riser string can also be monitored including the region adjacent to the ocean floor. By placing optical fibers sensors on diametrically opposite sides of the tube, one can determine the strains due to bending which occur during the dynamic vibration imposed by the ocean currents, i.e., VIV. Since the direction of bending is not know, several diametrically opposed optical fiber sets must be introduced into the composite tube to be assured of obtaining the maximum bending effect. With sufficient numbers of bending strain measurements, one can also determine the location of nodes (locations along the length without bending) and thus the periodic wave length. From maximum bending strains one can calculate the radius of curvature and thus the vibration amplitude. The vibration frequency can also be determined since the strain measurements are made as a function of time.

[0009] Many methods have been developed to inspect the integrity of metal and composite components including ultrasonic, radiography, and acoustic

emission. Each of these methods, however, does not address the need to inspect the component while performing the intended function in the marine environment. An in situ method is needed to monitor in real time the strains experienced by an offshore ~~oil~~ component such as a metal or composite riser. The fiber optics method of the current invention provides the capability to determine the state of fitness for service of these composite tubular components and provide the data needed to enhance safety and thus provide important operational safety quality assurance.

[0010] Visual inspection using a Remotely Operated Vehicle (ROV) is another method employed in offshore operations to inspect risers but a visual method is only superficial and does not provide ~~detailed data such as the strain data or temperature~~ needed to make precise engineering assessment of the structural integrity of the riser.

[0011] An Optical Time Domain ~~Reflectometry~~ Reflectometry (OTDR) technique for measuring the strain in a mooring rope is ~~has been~~ described in U.S. patent 6,999,641 B2 ~~application Ser. No. 10/430,058~~ in which plastic optical fibers are used to make direct measurement of the large axial strains typically experienced by offshore platform mooring ropes (3% and higher). Detailed discussion of the application of plastic optical fibers to the measurement of strain in large diameter ropes is presented in the following references which are incorporated herein by reference: Smith, D. Barton

and Williams, Jerry G.: Monitoring Axial Strain in Synthetic Fiber Mooring Ropes Using Polymeric Optical Fibers. 22nd International Conference on Offshore Mechanics and Arctic Engineering, Cancun, Mexico. June 8-13, 2003.

and by Jerry G. Williams and D. Barton Smith: "Direct Measurement of Axial Strain in Synthetic Fiber Mooring Ropes Using Polymeric Optical Fibers," Fourth International Conference On Composite Materials for Offshore Operations. Houston, TX, October 4-6, 2005. The strains in risers are significantly lower (less than 1%) and thus allow glass optical fibers to be used which exhibit much less attenuation (loss of light) than plastic optical fibers yet have a practical strain limitation well within the range of the riser and similar long slender structures~~application~~. The application of fiber optics to the riser application is significantly different from the rope application, however, the OTDR hardware required to make strain measurement is generally applicable and is similar to that used in the telecommunications industry to measure the location of broken optical fibers.

[0012] The deficiency of the visual inspection method is that it reveals nothing about the strain ~~or temperature~~ in the riser or provide adequate information to assess the criticality of Vortex Induced Vibration and most likely; ~~for~~ for operational safety concerns, would not be available during the most critical load history of the riser such as during storms. In addition, it is difficult and expensive to reliably inspect risers in situ using ROV

technology.

[0013] Traditional nondestructive inspection methods do not address the need to inspect and make measurements in situ in the marine environment.

[0013 A] Another long slender structure to which the strain measurement technology described above applies is to characterize dynamic behavior of large diameter ropes and cables subjected to water or wind generated vibrations. Large denotes a rope or cable sufficiently large in cross-section that bending strains are detectable as the long slender structure experiences vibration induced local bending. Large diameter mooring ropes, for example, are used for station keeping of offshore platforms and are subjected to VIV similar to that described above for risers. Large cables used as guide wires to stabilize tall towers is an example of a long slender structure subjected to wind generated vibrations.

[0013 B] A further application for the measurement of bending strains using the optical fiber system in long slender structures described herein is to characterize the buckling behavior of metal or composite spoolable pipe as it is injected into a small diameter annulus such as an oil well bore hole. Discussion of composite spoolable pipe technology can be found in the following reference: Jerry G. Williams and Alex Sas-Jaworsky II: "Composite Spoolable Pipe Development, Advancements, and Limitations,"

Offshore Technology Conference Paper 12029. Houston, Texas, May 1-4, 2000.

Spoolable pipe used as coiled tubing is typically taken off a large spool on which it has previously been wound and injected into a bore hole by the counter-rotating head of a coiled tubing injection rig. The counter-rotating heads of the Coiled Tubing Injector grip the pipe and impose axial compressive force to push the coiled tubing into the bore hole. Advanced applications of coiled tubing involve deployment into deviated and horizontal wells as well as vertical wells. Significant resistance to insertion can build up at the insert end of the coiled tubing requiring greater and greater injection force to keep it moving into the bore hole. As the resistance increases a condition is reached in which the applied compression force becomes sufficient to cause the pipe to buckle into a Spiral or Helical Buckle pattern (similar to a 3-dimensional "S" shape) inside the annulus. As large and larger axial compression forces are applied, the wave length (axial length of a repeated buckle pattern) of the spiral buckle gets shorter and shorter and a condition develops in which the spoolable pipe becomes locked in the annulus and cannot be withdrawn by the coiled tubing injector as it applies axial tension to retract the long slender structure.

[13 C] Many long slender structures such as risers are composed on multiple discrete length segments joined together by threaded couplings to form the structure. In the coupling transition region between jointed segments the

optical fiber is typically channeled into a coupling box attached to each end of the jointed segment. The optical fiber leads going into the coupling box are protected against bending and damage by the bonding agent and by the outer protective layer. The optical fiber leads are isolated against strain in the transition region by inserting them in a protective tube. Reflective interfaces may be placed at any location along the assembly including within a single segment or between multiple segments. For reflective interfaces located in different segments, the gage length is adjusted to account for the zero strain segment in the vicinity of the end termination and fiber optics connection box. Optical fiber signals are transmitted to the electronic optical signal monitoring instrumentation by means of an optical fiber or alternatively, the electronic optical signal monitoring instrumentation can be located remotely and digitized data transmitted by electric signal hard wire or radio signal to the accessible data acquisition system.

[0014] It is therefore an object of the invention to describe an optical fiber strain measurement system incorporating ~~optical-glass~~ optical fibers or large strain plastic optical fibers to determine the bending strain in long slender structures and to use the bending strain information for the purpose of determining the structures vibration or buckling characteristics. In the application, the optical fibers are integrally attached near to the outside of a metal or composite long slender tube-structure using a bonding

agent such as epoxy and protected from the environment including sea water and service damage by the bonding agent and an additional layer of polymer or elastomeric ~~rubber-like material~~ and thus experience identical strain to that imposed on the structure.

[0014 A] An alternative location for placement of optical fibers for metal spoolable pipe used as coiled tubing is to place them on the inside of the pipe. Positioning the longitudinal optical fibers on the inside of the pipe addresses the potential problem of damage to the optical fibers by the gripper blocks of a coiled tubing injector. For composite spoolable pipe, the optical fibers can be positioned anywhere in the cross-section if inserted during the manufacturing process. One process for attaching the optical fibers on the inside of long slender tubular is to prefabricate a cylindrical metal or composite foil containing an adhesive, such as a high temperature epoxy, on the outer surface of the foil and to locate longitudinal optical fibers on the foil at selected locations around the circumference of the foil. After fabrication of the metal coiled tubing, the foil would be pulled inside the tubing and the foil cylinder internally pressurized with a hot fluid or gas to force the foil to expand and to cure the bonding agent to the inside of the long slender tubular structure.

[0015] It is another object of the invention to provide a strain measurement system for assessing the vibration characteristics and structural integrity

of large ropes and cables ~~laminated composite tubular structure or the metal~~
~~to composite end connections based on strain measured using optical fiber~~
strain measurement the methods to determine the bending strain at selected
locations along the long large rope or cable. ~~described above.~~

[0016] It is another object of the invention to use ~~measure axial strains~~
~~using the time of flight optical fiber strain measurement methods including~~
Optical Time Domain Reflectometry (OTDR) ~~fiber optics method to determine~~
the bending strains in long slender structures by placing optical fibers
along the axis of the metal or composite long slender structure ~~tubular~~
starting at one end and traversing to the other end and if needed, to
provide greater strain resolution; to loop the optical fiber back and forth
as many times as needed to amplify the displacement magnitude.

[0017] It is another object of the invention to provide a method using the
Optical Time Domain Reflectometry (OTDR) fiber optics method to measure
bending average strains in a long slender metal or composite structure made
up of jointed segments ~~metal or composite tubular structure including~~
~~measurement of average circumferential strains as well as average axial~~
~~strains including a single or multiple over a long segments length of the~~
~~composite tube including the entire length from end to end.~~

[0018] ~~It is another object of the invention to use the Bragg Diffraction~~

~~Grating fiber optics method to measure local strains in a composite tubular structure in any direction, either circumferential or axial or at any angle to the axis of the tube, determined by design or test to be critical.~~

[0019] ~~It is another object of the invention to provide a structural integrity monitoring system to determine strain concentrations and local anomalies by measuring average strains, either circumferential or axial or at any angle to the axis of the tube, in the metal to composite end connection of composite tubulars including risers using the Optical Time Domain Reflectometry (OTDR) optical fiber strain measurement method. The preferred method is to wrap the optical fibers onto the outside of the composite structure and to attach the optical fiber to the composite material using a bonding agent such as epoxy and to protect the optical fiber by the bonding agent and with an additional outside protective layer of polymer or rubber like material.~~

[0020] ~~It is another object of the invention to provide a structural integrity monitoring system for the metal to composite end connection commonly used in composite tubular construction using the Bragg Diffraction Grating optical fiber strain measurement method described above to measure local strains in the composite to metal end connection, either circumferential or axial or at any angle to the axis of the tube to determine local strain concentrations and local anomalies. The preferred~~

~~method is to wrap the optical fibers onto the outside of the composite structure and to attach the optical fiber to the composite material using a bonding agent such as epoxy and to protect the optical fiber by the bonding agent and with an additional outside protective layer of polymer or rubber-like material.~~

[0021] It is another object of the invention to provide a ~~technique~~ system utilizing Optical Time Domain Reflectometry (OTDR) and axially oriented optical fibers to determine the magnitude of bending strains imposed on ~~measure the dynamic response of metal or composite~~ tubulars subjected to cyclic vibration such as induced in a metal or composite riser subjected to ocean currents, i.e., Vortex Induced Vibrations (VIV).

[0022] ~~It is another object of the invention to provide a method for determining the magnitude of large bending strains induced by Vortex Induced Vibrations (VIV).~~

[0023] It is another object of the invention to provide a fiber optics system ~~method~~ to measure the large axial ~~and~~ bending strains typically imposed on long slender metal or composite components such as ~~spoolable composite pipe~~ during deployment from a spool and into and out of a small diameter annulus using plastic optical fiber composed of polymeric materials including polymethyl methacrylate and perfluorocarbon, which have strain

capabilities exceeding 5-percent with relatively low attenuation.

[0023A] It is another object of the invention to provide a fiber optics method to measure the bending strains imposed on spoolable composite pipe during deployment into and out of a small diameter annulus for the purpose of preventing a condition of lock-up of the pipe inside the annulus.

~~[0024] It is another object of the invention to provide the design architecture for a coupling box to be attached to each end of the tube into which optical fibers are centrally located and protected. The optical fiber leads going into the coupling box are protected against bending and damage by the bonding agent and by the outer protective layer. The optical fiber leads are isolated against strain in the transition region by inserting them in a protective tube.~~

~~[0025] It is another object of the invention to provide a fiber optics coupling connector which bridges between individual joints of tubing. Such connector carries the optical fiber signal from the current joint as well as from tubing joints located at more remote distances from the data acquisition system and eventually to the surface.~~

~~[0026] It is therefore another object of the invention to provide a fiber optics method using Bragg Diffraction Grating to provide in situ~~

~~measurements of the temperature of a tubular in the marine environment including metal and composite risers used in offshore drilling and production operations.~~

[0027] It is another object of the invention to provide a means to incorporate multiple fiber optics ~~bending~~ strain sensors within a long slender structure or segment thereof.~~single riser joint.~~

[0028] It is therefore an object of the invention to provide a capability through multiplexing of the Optical Time Domain Reflectometry (OTDR) and Bragg Diffraction instrumentation to allow numerous optical fibers or multiple reflections within the same fiber to be monitored using a single or multiple instruments.

SUMMARY OF THE INVENTION

[0029] In accordance with the present invention, there is provided a method for in situ measurement of the bending strain ~~and temperature~~ of metal and composite tubulars located in the marine environment using optical fiber techniques including Optical Time Domain Reflectometry (OTDR) or Bragg ~~D~~iffraction ~~G~~ratings. The method uses these rapidly obtained bending strain measurements to determine the dynamic characteristics of long slender structure or to determine the spiral buckle characteristics and pending

state of lock-up in spoolable pipe deployed into a small diameter annulus.
~~provides the capability to make axial, circumferential and off-axis strain~~
~~measurements on the body of the riser and critical strain measurements in~~
~~the metal to composite joint region typically used in composite risers.~~
~~Through engineering analysis of the optical strain measurements,~~ The method
provides the capability to determine the local bending strain along the
length of the structure caused by wind or water induced disturbances and
through engineering analysis to determine structural dynamic response
characteristics including the vibration frequency, vibration peak amplitude,
and periodic node to node wave length. ~~of Vortex Induced Vibrations (VIV)~~
~~imposed by marine ocean currents.~~ For example, one can use the method to
determine the vibration characteristics of offshore risers subjected to
Vortex Induced Vibrations (VIV) imposed by marine ocean currents. In
another application the bending strain measurements can be used to determine
the dynamic response of large diameter ropes or cables subjected to wind or
water induced vibrations. The optical fibers of either glass or polymeric
composition are located near the external surface of the long slender
structure following fabrication and bonded directly ~~on the outside of either~~
~~metal or composite risers following fabrication and bonded directly to the~~
~~outer surface of the riser structural body and subsequently encapsulated in~~
~~an outer protective cover. For long slender composite structures, the~~
~~optical fibers may alternatively be integrated into the structure body and~~
~~co-cured with it. —Bragg gratings are particularly valuable for making~~

local strain ~~and temperature~~ measurements while the Optical Time Domain ~~Reflectometry~~ Reflectometry method is ideally suited for making global strain measurements such as the average strain over ~~the~~ a discrete segment of a long slender structure. ~~entire length of a riser and for VIV monitoring.~~ Multiplexing of the light signal allows monitoring of several ~~plastic~~ optical fibers as well as monitoring multiple discrete and multiple segments within a single optical fiber. ~~using a single light time of flight instrument.~~ The strain within discrete segments is facilitated by placing optical reflective interfaces at selected locations along the length of the optical fiber. Strain measurements are transmitted to the surface either by a continuous optical fiber light path or by telemetry of a digitized signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] A complete understanding of the present invention may be obtained by reference to the accompanying drawings, when considered in conjunction with the subsequent, detailed description, in which:

[0031] FIG. 1 is a side view of an of a long slender metal or composite tubular structure indicating the positioning of fiber optics apparatus required to make bending strain measurements; and

[0032] FIG. 2 is a cross-sectional view of a long slender ~~the~~ metal or

~~composite structure tubular illustrated in FIG. 1 illustrating showing the positioning of longitudinal optical fibers optics apparatus around the circumference of the metal or composite tubular illustrated in FIG. 1; and relative to the metal or composite tubular structure.~~

[0032 A] FIG. 3 is a schematic of a coiled tubing rig injecting spoolable pipe into a small diameter annulus illustrating the state of spiral or helical bucking induced by axial compressive forces imposed on the long slender spoolable pipe structure restrained laterally by the small diameter annulus.

[0033] For purposes of clarity and brevity, like elements and components will bear the same designations and numbering throughout the FIGURES.

DESCRIPTION OF THE PREFERRED EMBODIMENT

~~[0034] For purposes of clarity and brevity, like elements and components will bear the same designations and numbering throughout the FIGURES.~~

[0035] Now referring to FIG. 1, which is a side view of a Long Slender Metal or Composite Structure Tube 10 indicating the positioning of fiber optics apparatus required to provide strain ~~and temperature~~ measurements. The Long Slender Metal or Composite Structure 10 is a single segment of a long

assembly of similar structures joined together with Threaded End Coupling 22
located on End Termination 18 or by other means. Axial Optical Fibers 12
~~in Body of Tube 12~~ are positioned along the axis of the Long Slender Metal
or Composite Structure Tube-10 and the glass or plastic optical fibers ~~are~~
~~etched~~ have Optical Reflective Interfaces 14 to provide capabilities
consistent with either time of flight instrumentation such as Optical Time
Domain Reflectometry ~~Reflectometry~~ or as gratings for Bragg Diffraction
~~Grating strain~~ measurements. ~~The Optical Time Domain Reflectometry optical~~
~~fiber has a~~ Optical Reflective Interface 14 may be placed at each ~~the end~~
of the optical fiber which is rigidly attached to the long slender structure
making possible a gage length of the entire length of the Long Slender
~~Metal or Composite Structure Tube-10~~ and at intermediate positions along
the length of the Axial Optical Fiber 12 to provide shorter gage lengths.
Structural analysis programs can be used to predetermine the expected
vibration characteristics and guide the selection of the placement of
Optical Reflective Interfaces 14. ~~The~~ Bragg diffraction grating is a
localized diffraction grating within the optical fiber on the order of 1-
inch in length and thus provides measurements of local strain. ~~As with~~
~~axially oriented optical fiber, strain measurements can be made using either~~
~~Optical Time Domain Reflectometry or Bragg diffraction grating techniques~~
~~and optical fiber reflective interfaces.~~ The optical signal generated at
Optical Reflective Interfaces 14 are channeled into a Fiber Optics
Connection Box 20 located each end of the Long Slender Metal or Composite

Structure 10 and subsequently into other Fiber Optics Connection Boxes 20 located on adjacent segments. The laser light is transported into the optical fiber from a source conveniently located near the end of the Long Slender Metal or Composite Structure 10 and the reflected response is transmitted back to the electronic optical signal monitoring instrumentation for signal interpretation and strain calculations. It may be preferred when monitoring the strain in structures located in remote locations to place the electronic optical signal monitoring instrumentation and laser light source in near proximity to the remotely located structure and transmit a digitized form of the interpreted signal by electrical or radio signal to a more accessible location.

[0036] Further referring to FIG. 2, which provides a cross-sectional view of the Long Slender Metal or Composite Structure 10 with rigidly attached Axial Optical Fibers 12. ~~and integrated optical fibers. The tube with has a Metal or Laminated Composite Structure 30. usually has a Tube Interior Liner 32.~~ Axial Optical Fibers 12 may consist of a single fiber which traverses along the length of the Long Slender Metal or Composite Structure 10 including for a discrete length of from one end of the segment to the other. For greater strain measurement sensitivity, the optical fiber may be looped back and forth to provide a longer gage length, Optical Fiber Looped End to End 36. ~~allows an increase in the strain sensitivity of the Optical Time Domain Reflectometry method by providing a longer gage length. A~~

single optical fiber traversing from one end of the segment to other end
placement of optical fiber is considered adequate for ~~long~~ tubes with long
length segments such as risers used in offshore exploration and production.

[0036 A] Further referring to FIG. 3, which provides a schematic view
illustrating coiled tubing equipment deploying Spoolable Pipe 42 from a
Storage Spool 44 into a Small Diameter Annulus 50. The Coiled Tubing
Injector 40 grips the Spoolable Pipe 42 controlling the descent during
insertion into the predrilled low friction vertical section of the Small
Diameter Annulus 50. As the Small Diameter Annulus 50 deviates from
vertical and frictional forces exceed the weight of the Spoolable Pipe 42
suspended in the Small Diameter Annulus, the Coiled Tubing Injector 40
applies compressive force onto the Spoolable Pipe 42 to force it further
into the Small Diameter Annulus 50. The Small Diameter Annulus 50 is
typical created by a Mud Motor Drilling Tool 46 driven by the circulation of
mud under high pressure which flow down the Spoolable Pipe 42 and back to
the surface in the space between the Spoolable Pipe 42 and the Small
Diameter Annulus 50. Extension of the length of the Small Diameter Annulus
50 is accomplished by the rotary action of the drill bit of the Mud Motor
Drilling Tool 46 as it breaks up the earth formation. The compressive force
of the drill bit upon the formation required for drilling is created by the
pushing force of the Coiled Tubing Injector 40 and the weight of the
Spoolable Pipe 42 suspended in the vertical portion of the Small Diameter

Annulus 50. Small particles broken from the formation are carried to the surface with the circulation of the drilling mud. It is common practice in modern petroleum drilling operations to extend a Small Diameter Annulus 50 from a vertical into a deviated or horizontal direction as illustrated in FIG 3. As the horizontal portion of the Small Diameter Annulus 50 grows relative to the vertical portion, greater frictional forces are developed and the Coiled Tubing Injector 40 must apply increasing greater compressive force on the Spoolable Pipe 42 to advance the Mud Motor Drilling Tool 46 further into the Small Diameter Annulus 50. A stability condition develops in which the Spoolable Pipe 42 begins to buckle in the Small Diameter Annulus 50. As greater and greater compressive forces are applied, the Spoolable Pipe 42 buckles in a Spiral or Helical Buckle 48 illustrated in FIG 3. As greater and greater compressive force is applied and more and more friction is developed, a buckling condition is reached at which the force required to retract the pipe back out of the Small Diameter Annulus 50 are greater than the pulling force capability of the Coiled Tubing Injector 40 or the strength of the Spoolable Pipe 42 and a condition of lock-up occurs. Coiled tubing Lock-up is a serious problem and preventive measures to avoid this condition are important considerations.

[0037] The capability to provide bending and vibration information for loads imposed by Vortex Induced Vibrations (VIV) and other dynamic disturbances is provided by positioning ~~imposing~~ multiple sets of optical fibers along the

longitudinal axis of the long slender structure spaced around the circumference with Longitudinal Optical Fiber Optics-Circumferential Spacing 34 illustrated in FIG. 2. For bending strain measurements it is necessary to have strain information from opposite sides of the tube and to capture the maximum bending strain; it is necessary to have multiple sets of back to back optical fiber strain gages. Each ~~with~~ set of Axial Optical Fibers 12 is located on the structure at opposite ends of an imaginary line drawn perpendicular to the longitudinal axis of the long slender structure and through the structure centroid thereby enabling the measurement of the maximum bending strain imposed during dynamic loading. ~~axial oriented optical fibers. For illustration, in a 45-degree spacing around the circumference is shown in FIG 2 thus providing 4 sets of bending strain measurements. For bending strain measurements it is necessary to have strain information from opposite sides of the tube as provided by a 45-degree and other spacings.~~

[0038] Axial The Optical Fibers 12 can be placed onto the outside of a Long Slender Metal or Composite Structure Tube-10 following the tube structural fabrication or optionally for composite and rope or cable structures; integrated during the structure's manufacturing. The optical fibers can be bonded using an adhesive such as epoxy directly to the tube and a Protective Outer Layer and Fluid Barrier 16 is laid over the optical fiber to further protect it from impact and the ~~marine~~ environment. Similar

protection can be ~~is provided in the transition of the~~ Axial Optical Fiber ~~12 in Metal to Composite End Coupling 18 and in the transition into the~~ Fiber Optics Connection Box 20 located on the End Termination 18 illustrated on Fig. 1 by inserting it into a tube. ~~overlaying the optical fibers with a polymeric or elastomeric material.~~ The Axial Optical Fiber 12 thus does not experience strain in the region outside the gage length define as the length between Optical Reflective Interfaces. As discussed above, for spoolable metal coiled tubing, an alternative location for the optical fibers is on the inside of the tubing.

[0039] A Long Slender Metal or Composite tube ~~Structure~~ 10 is normally connected to adjacent tubes using a Threaded End Connection 22. In near proximity to the end connection is located a Fiber Optics Connection Box 20 which serves as the termination point for Axial Optical F ~~fibers~~ 12 and serves as the connection junction for transferring optical signals from one ~~tube~~ structural segment to the next ~~tube~~ segment and eventually to the surface and into a Optical Time Domain ~~Reflectometry~~ Reflectometry, ~~or~~ Bragg ~~Diffraction Grating~~ or other optical signal interpretation instrument ~~which is used to process the laser light reflected signal~~ data. An alternative way to transfer the strain ~~and temperature~~ data to the surface is to locate the Optical Time Domain Instrument or Bragg Diffraction Grating instruments in a control box attached to the tube, and digitize the data and send it to surface with electronic telemetry or electrical ~~hard~~ wire.

[0040] The basic principals of the invention which measures the dynamic response of long slender structures involves a system composed of: (1) attachment of optical fibers (glass or polymeric) ~~nearte~~ the exterior outside of the body of a ~~the metal or laminated composite pipe~~ long length slender metal or composite structure, (2) the placement of reflective interfaces at selected locations along the length of the optical fibers, (3) introduction of a laser light source into the optical fiber for purposes of generating a reflective or frequency based light response at the reflective interface, (4) electronic optical signal monitoring instrumentation to analyze the light signals reflected or transmitted from optical reflective interfaces in the optical fibers for the purpose of determining the bending strain within predetermined segments along the length of the long slender structure, and (5) fiber optics or electronic data transmission link to transport the reflected optical fiber light signal data to the electronic optical signal monitoring instrumentation.

[0040 A] The optical fibers are rigidly attached to the long slender structure ~~protection of the optical fibers by the bonding agent and additional protection can be provided by a secondary outer protective layer such as is typically required for other purposes including sealing a composite tube laminate against fluid intrusion.~~ , and ~~(3) application of the Optical Time Domain Reflectometry (OTDR) and/or Bragg Diffraction~~

~~Grating measurement technology to measure strain and temperature, (4)~~
~~protection of t~~The optical fiber leads from the end of the gage section into
a central fiber eOptics eConnection bBox 20 should be isolated again strain
since it is important not to impose strain in the optical fiber outside the
gage section and it can be provided protection by insertion into a carrier
tube. , and (5) method for transferring the data to the surface. For
application of the bending strain measurement system for dynamic
characterization of ropes and cables, the preferred method is to integrate
the optical fibers into the construction of the rope or cable during
manufacture. One method is to place the optical fiber on or near the outer
surface of the rope or cable and overlay a protective braid or polymeric
coating as is a common practice in rope and cable construction to protect
the rope or cable. The outer braided cover commonly used in the
construction of large diameter mooring ropes deployed for station keeping on
offshore platforms is tightly applied and will provide sufficient friction
during loading to impose upon the axial optical fiber near identical axial
strain to that experienced [0036 A] Further referring to FIG. 3, which
provides a schematic view illustrating coiled tubing equipment deploying
Spoolable Pipe 42 from a Storage Spool 44 into a Small Diameter Annulus 50.
The Coiled Tubing Injector 40 grips the Spoolable Pipe 42 controlling the
descent during insertion into the predrilled low friction vertical section
of the Small Diameter Annulus 50. As the Small Diameter Annulus 50 deviates
from vertical and frictional forces exceed the weight of the Spoolable Pipe

42 suspended in the Small Diameter Annulus, the Coiled Tubing Injector 40 applies compressive force onto the Spoolable Pipe 42 to force it further into the Small Diameter Annulus 50. The Small Diameter Annulus 50 is typical created by a Mud Motor Drilling Tool 46 driven by the circulation of mud under high pressure which flow down the Spoolable Pipe 42 and back to the surface in the space between the Spoolable Pipe 42 and the Small Diameter Annulus 50. Extension of the length of the Small Diameter Annulus 50 is accomplished by the rotary action of the drill bit of the Mud Motor Drilling Tool 46 as it breaks up the earth formation. The compressive force of the drill bit upon the formation required for drilling is created by the pushing force of the Coiled Tubing Injector 40 and the weight of the Spoolable Pipe 42 suspended in the vertical portion of the Small Diameter Annulus 50. Small particles broken from the formation are carried to the surface with the circulation of the drilling mud. It is common practice in modern petroleum drilling operations to extend a Small Diameter Annulus 50 from a vertical into a deviated or horizontal direction as illustrated in FIG 3. As the horizontal portion of the Small Diameter Annulus 50 grows relative to the vertical portion, greater frictional forces are developed and the Coiled Tubing Injector 40 must apply increasing greater compressive force on the Spoolable Pipe 42 to advance the Mud Motor Drilling Tool 46 further into the Small Diameter Annulus 50. A stability condition develops in which the Spoolable Pipe 42 begins to buckle in the Small Diameter Annulus 50. As greater and greater compressive forces are applied, the

Spoolable Pipe 42 buckles in a Spiral or Helical Buckle 48 illustrated in FIG 3. As greater and greater compressive force is applied and more and more friction is developed, a buckling condition is reached at which the force required to retract the pipe back out of the Small Diameter Annulus 50 are greater than the pulling force capability of the Coiled Tubing Injector 40 or the strength of the Spoolable Pipe 42 and a condition of lock-up occurs. Coiled tubing Lock-up is a serious problem and preventive efforts are important to avoid this condition.

[0041] Glass or polymeric optical fibers are positioned at selected locations on the outside surface of the ~~Long~~ ~~Slender~~ ~~Metal~~ or ~~Composite~~ ~~Structure~~ 10. Glass fibers have lower attenuation than polymeric fibers and are the preferred optical fiber of choice for measuring small strains (less than approximately 1-percent) while plastic optical fibers such as polymethyl methacrylate or perfluorocarbon, which have strain capabilities exceeding 5-percent and relatively low attenuation for a polymeric optical fiber, are appropriate for large strain measurements. In general, the glass optical fiber capability is adequate for most high performance tubulars proposed for use in the oil industry such as risers. The utilization of fiber optics to measure peak strains in spoolable composite pipe would normally require polymeric optical fibers since the strains imposed during spooling and service typically exceed 1-percent.

[0042] It is considered sufficient to determine the general state of structural integrity by measuring critical bending strains experienced on the exterior of a long slender metal or composite structure. Integrating optical fibers into a the composite laminate body can be accomplished, but is a difficult complication to impose during the manufacture of the composite structure (filament winding or other process); especially to maintain the integrity of the optical carrier leads. Fortunately, it is considered sufficient to determine the general state of structural integrity by measuring critical strains experienced by the exterior of the metal or composite structure tube. The preferred technique is to attach the optical fibers on the exterior of the structure following manufacture in a separate operation. ~~As discussed below, a variety of locations are proposed for the location of optical fibers including on the tube body and on the metal to composite end connection.~~ The sequence is to finish the manufacture of the tube including end coupling and to carefully place the optical fibers onto the outside body of the tube and end coupling using a bonding agent such as epoxy. In this process, the optical fiber end leads are also carefully extended into the Fiber Optics Connection ~~Box 20~~. A low modulus resin or elastomer may be used to bond the fiber optics ends to the tube in the region of the end connection and if necessary the optical fiber can be inserted in a protective sleeve for protection and to eliminate strain imposed on the optical fiber in this transition region. Once the fibers are so located and bonded in place, an additional protection layer may be placed

over this assembly. Such a protective outer layer is typically used for high performance tubular products such as deepwater ~~composite~~-risers in order to protect the ~~composite~~-structure during handling and for composite risers to prevent the ingress of sea water into the composite.

[0043] A discussion of the specific bending strain measurements of interest for primary tube structure applications are outlined below.

[0044] Tube Body Axial Strain Using OTDR or Bragg Diffraction Gratings

[0045] The axial strain in the body of the pipe is measured in a discrete local region using Bragg ~~Diffraction~~ ~~Gratings~~ while the average strain over a longer section of the tube is measured using the Optical Time Domain ~~Reflectometry~~Reflectometry (OTDR) strain measurement method. The OTDR method measures the time of flight for light reflected from reflective interfaces placed at selected locations along the length of the optical fiber and thus directly measures, through calibration, the change in the length between the two interfaces. These light reflection interfaces can be placed to provide strain measurements of short as well as long gage lengths. In one application the reflective interfaces would be placed at each end of an optical fiber rigidly attached along the length of a metal or composite tube and thus provide a strain measurement of the average strain over the entire length of the long tube such as a riser used in offshore drilling and

production operations. ~~from one end to the other end of the composite tube~~
~~and thus provide a strain measurement of the average strain over the entire~~
~~length of the composite tube such as a riser.~~ If greater accuracy is needed,
the optical fiber ~~could traverse~~ can be traversed back and forth from one
~~end to end~~ of the tube to the other as many times as is needed to provide
the required strain measurement accuracy. ~~a longer gage length~~

[0046] Measurement of the longitudinal strain in the composite tube provides
valuable information about the state of the "fitness for service" of the
composite tube when compared to design allowables and expected threatening
conditions. ~~A further manifestation of the technology is for the m~~
Measurement of strains imposed by Vortex Induced Vibration (VIV) is, a
phenomenon of intense interest to oil company operators concerned about the
safety of production and drilling risers. By placing optical fibers sensors
on diametrically opposite sides of the tube, one can determine the strains
due to bending which occur during the dynamic vibration imposed by the ocean
currents, i.e., VIV. Since the direction of bending is not know, several
diametrically opposed optical fiber sets must be introduced into the
composite tube to be assured of obtaining the maximum bending effect. Four
or more sets of diametrically opposite optical fiber strain gage sets could
be used to provide an axial optical fiber every 45-degrees or less around
the circumference. Typically, the period of the imposed vibration is on the
order of several seconds which is consistent with the capability to measure

and record strains by the OTDR or Bragg diffraction grating method.

[0047] With regard to VIV induced strain, the OTDR method using longitudinally-positioned, diametrically-opposite fiber optic sensor sets applies equally well to either metal or composite risers. The fiber optics technology application described herein would have an important role in enhancing the safety of offshore drilling and production operations.

[0048] ~~Tube Body Axial Strain Using Bragg diffraction grating~~ As discussed above, optical fibers with Bragg diffraction gratings etched into an optical fiber can be used to measure local strain anomalies at selected locations along the length of the tube. A single optical fiber can have several diffraction gratings etched on it. The data acquisition system can individually interrogate each grating and thus provide multiple local strain measurements using the same optical fiber.

[0049] ~~Tube Body Circumferential Strain using OTDR or Bragg Diffraction Grating~~

[0050] ~~Measurement of the circumferential or off-axis strain can also be important for structural performance monitoring. The complete state of stress can be measured using a rosette of fiber optics (0/90/45) measuring strain in a common region of the tube. In this case the Bragg Diffraction~~

~~Grating method would be the preferred technique. One of the advantages of measuring the circumferential strain is that it provides an indicator of local anomalies indicative of local damage or structural degradation. The optical fiber would be wound around the outside of the composite structure at an angle of approximately 65 to 90 degrees to the axis of the tube. A single gage length with reflective surfaces at each end of the tube is one configuration productive for overall monitoring of the structural health of the structural tube. It may also be desirable to provide multiple reflective interfaces on a single optical fiber to capture information about discrete segments along the length of the tube. To obtain the necessary sensitivity, it will be necessary to make several revolutions between reflective interfaces. The optical fiber wind angle will determine the length of tube to be considered for each discrete gage length.~~

[0051] ~~Metal to Composite Joint Strain Monitoring~~

[0052] ~~Most high performance composite tubular components such as risers are connected together using a metal (steel or titanium) threaded coupling. The metal to composite transition coupling is often considered the most critical part of the composite tube. A trap lock fitting involving winding composite fiber into circumferential recesses in the metal is one of several end couplings proposed for composite risers. The structural integrity monitoring method described herein is to monitor the strain in this region to detect if~~

~~disbonds and damage propagation have occurred. Optical fibers are wound around the outside of the composite structure in any direction or location desired as determined by design or experience to be the most critical area. Optical fibers wound in the circumferential direction are particularly effective using the OTDR measurement technique. The optical fibers are wound at an angle of 80 to 90 degrees relative to the axis of the tube. Several revolutions of the optical fiber are used between placement of reflective surfaces to allow a long gage length and high sensitivity of the strain measurement. Although this provides an average circumferential strain measurement, local strain anomalies will usually be sufficiently large to detect by the method. Bragg diffraction gratings can also be used to measure local strains in any direction desired.~~

[0053] End Connection Optical Fiber Integration

[0054] The optical fibers are integrated into a central connection box mounted on the side of the composite or metal structure~~tube~~. Optical fibers are protected in the region of the connection box by an~~the~~ outer protective layer applied to the outside of the tube. In the region of transition from the point of measurement to the connection box, the optical fibers are inserted in a sleeve to prevent strains in the transition region from adding to the strains imposed in the gage section. Connector terminations developed by the telecommunications industry are used to collect large bundles of

optical fibers. Optical signals from more remote tube sections are also introduced into the termination box. The signal from remote tubes are carried between connections using separate lines which can be located in a protective tube inside the tube outer protective layer or by a separate line attached to the tube.

[0055] Signal Transfer from Remote Sections of the ~~Mooring Rope~~ Long Slender Structure

[0056] Two approaches are available for transporting the optical signal to the surface. The first approach is to provide continuous optical fiber paths to the surface. This method requires that optical fiber connections be made between individual segments~~joints~~ of the long slender structure~~riser~~ during installation. The second method is to locate the ~~OTDR~~ electronic optical signal monitoring instrumentation in close proximity to the ~~riser~~ long slender structure and use hard wire or remote telemetry to transfer the digital data signal to the surface. As required, repeaters can be used to relay and amplify the signal.

[0056 A] The preferred method for using optical fiber strain measurement methods involves the measurement of reflected light signals. For some applications of the technology it may be preferable to use the principles described herein based on transmitted light signals.

[0057] Thus, in summary, it can be seen that ~~what is the invention~~ provides ~~in this invention~~ an in situ structural integrity monitoring system utilizing fiber optics technology to ~~provide~~ generate detailed bending strain data used: (1) to characterize the vibration characteristics of long slender structures subjected to dynamic disturbances imposed by water or wind generated loads and (2) the bending and pending lock-up conditions of spoolable pipe injected into an annulus. ~~and temperature information for~~ Long slender structures include but are not limited to metal and composite tubulars, particularly risers, used in deepwater petroleum drilling and production operations, and ropes and cables. ~~Through eEngineering~~ interpretation of the strain data, for example, ~~the method~~ provides the capability to determine the vibration characteristics of drilling and production risers subjected to ~~magnitude of bending strains induced by~~ Vortex Induced Vibrations (VIV) caused by strong ocean currents including ~~and the vibration amplitude, frequency, and node to node-~~ wave length.

[0058] Since other modifications and changes varied to fit particular operating requirements and environments will be apparent to those skilled in the art, the invention is not considered limited to the examples chosen for purposes of disclosure, and covers all changes and modifications which do not constitute departures from the true spirit and scope of this invention.

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[0059] Having thus described the invention, what is desired to be protected by Letters Patent is presented in the subsequently appended claims.